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A morphing wing is a multidisciplinary system that includes a shape changing flexible structural subsystem, an active material subsystem that generates the desired shape changes, an electronics subsystem that drives the active materials to achieve the desired shape changes. As opposed to fixed wing structures in which the aerodynamic and structure integration for the entire wing is the most important interaction mechanism, in the case of a morphing wing structure the interaction of the structures and aerodynamics occur in conjunction with the active material and electronic subsystem interactions that involve transfer of energy from a source to the shape changing structure and vice versa.

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ENERGY BASED TOPOLOGY OPTIMIZATION OF MORPHING WINGS A MULTIDISCIPLINARY GLOBAL/LOCAL DESIGN APPROACH

AFOSR GRANT FA9550-04-1-0124

Final Report for the Period March 1, 2004 to December 31, 2006

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Executive Summary

A morphing wing is a multidisciplinary system that includes a shape changing flexible structural subsystem, an active material subsystem that generates the desired shape changes, an electronics subsystem that drives the active materials to achieve the desired shape changes. As opposed to fixed wing structures in which the aerodynamic and structure integration for the entire wing is the most important interaction mechanism, in the case of a morphing wing structure the interaction of the structures and aerodynamics occur in conjunction with the active material and electronic subsystem interactions that involve transfer of energy from a source to the shape changing structure and vice versa. This apparently four way interaction results in a highly coupled system, in which everything affects everything else. Hence, the best system design cannot be achieved by simply optimizing system components individually, but by allowing some of the subsystems to become slightly suboptimal, which in turn, can yield gains that sum up to an overall improvement. In this research we investigated a Multidisciplinary Design Optimization (MDO) strategy for morphing wing design to exploit subsystem interactions. We investigated and developed analytical models that address the various interactions, particularly energy flow, among these subsystems. These analytical models are used to formulate the topology optimization problem of a morphing wing. These ideas were also used to optimize the diamond cell mechanisms for the NexGen batwing concept for morphing wings. This research lead to a new concept for a morphing wing called here a warping wing. Several analytic, computational and experimental studies were conducted to investigate the warping wing. These studies include the investigation of a novel thermoplastic morphing sandwich skin configuration.

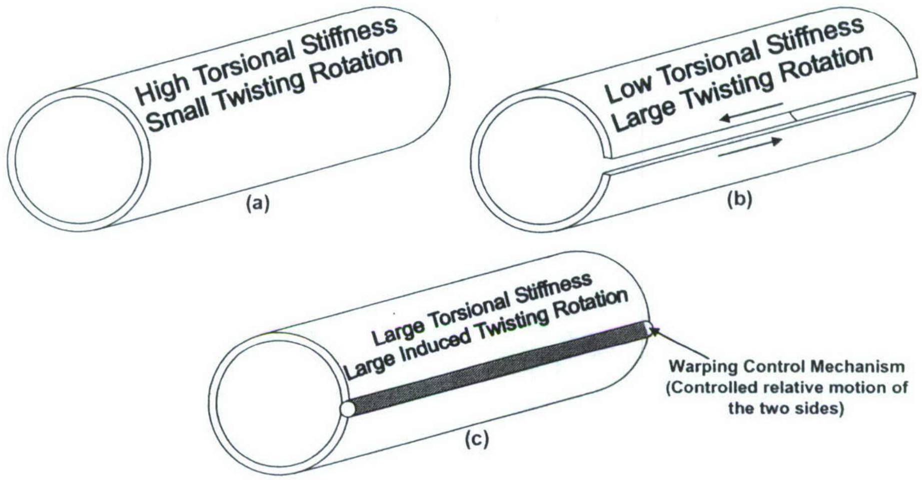
Project Summary

Warping Wing

The quest for morphing aircraft structures to enable efficient multi-point operation of aircraft, and possibly multi-functional operation, poses significant technical challenges for the structural designer. Structural design has been largely driven by strength and stiffness requirements. For conventional aircraft construction materials (metals and fibre reinforced plastics), the allowable strain limits are usually quite small, and as such stiffness and strength requirements are frequently aligned. Thus, all conventional aircraft structural designs are geared towards high stiffness, and as such would be extremely difficult to change shape elastically without prohibitively large actuation forces.

One class of structural solutions, for morphing wings, is to introduce hinges and allow rigid body motions of parts of the structure. Apart from the issues attending the design of the hinges and actuation mechanisms, such solutions may require significant straining of the wing skin and necessitates the introduction of complex skin design concepts. A new morphing wing design called warping wing was developed during the project that addresses this difficulty. The warping wing concept avoids the need to introduce large strains into the skin, while allowing for large twist deformations of the wing (or sections of the wing). The concept also modifies conventional

wing structural layout minimally, and introduces minimum additional mechanical complexity, thus reducing production costs and increasing reliability.



Concept for large torsional stiffness and large twist-angle beam section.

Figure 1: Concept of the warping wing.

The basic concept is illustrated in Figure 1, where Figure 1a represents a stiff closed section, figure 1b represents an over-flexible open section that is easy to twist but is unacceptable from aeroelastic point of view; finally, figure 1c depicts the warping concept where the section is open but the amount of warping between the two parallel edges is controllable using a self-locking mechanism. During flight, the mechanism is locked causing the cross section to operate as a close cross section with high torsional stiffness. During morphing, the mechanism induces warping in the cross section leading to induced twist along the span.

Although the concept is straightforward for such simple beam sections, design details in the case of actual wing construction are not trivial. Provisions for sliding of the skin and rotation of stiffeners and spars need to be carefully design. The finished scaled carbon fibre skin wing is shown in Figure 2.

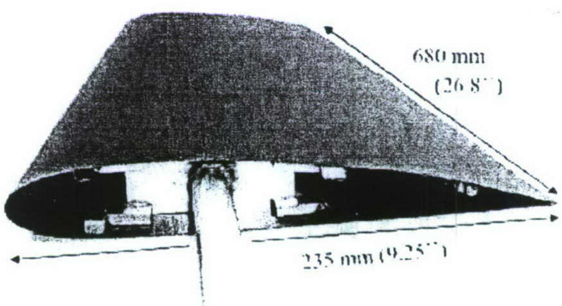


Figure 2: View of the warping wing model.

The relationship between induced warping and induced twist across the span is shown in Figure 3.

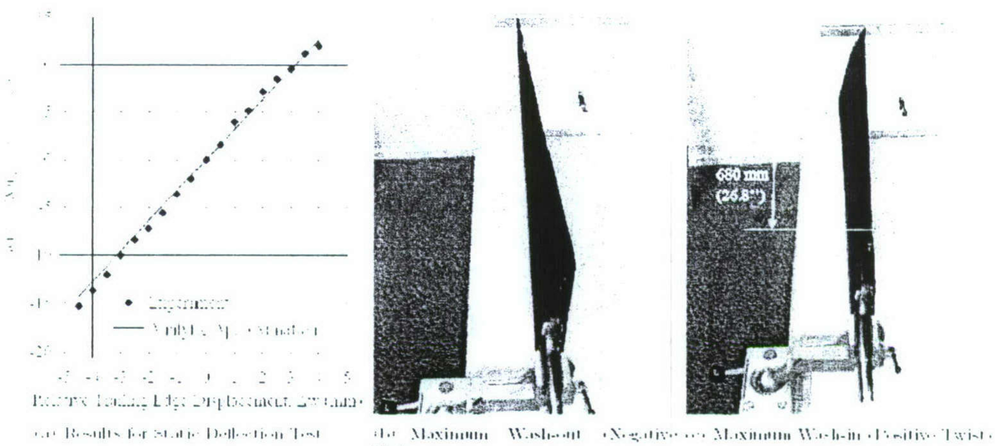


Figure 3: Wing twist vs. warping displacement.

It is seen that substantial amount of twist can be obtained by applying relatively small warping displacements. Finally, wind tunnel test results are shown in Figure 4

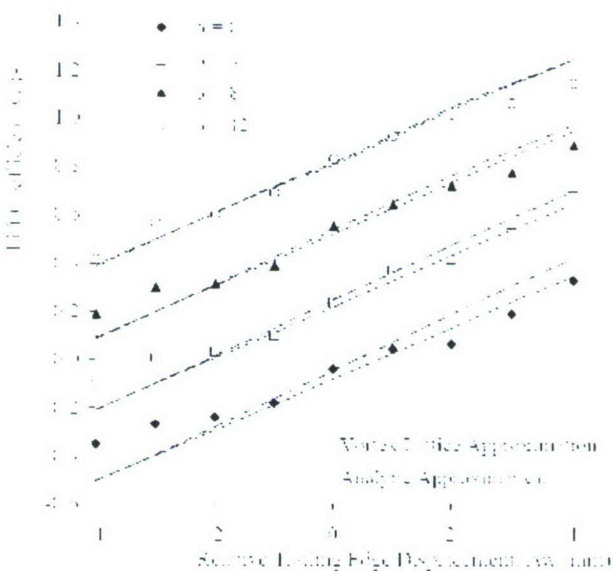


Figure 4: Lift increment due to induced warping [1].

These test show that substantial increase in lift coefficient is possible using this concept. A thorough description of the concept and the model generation is given in reference [1].

Apart from use for UAV applications, the proposed warping wing concept can be effectively used as a morphing winglet for military transport vehicles and has strong potential for use in adjustable rotor blades.

Morphing Thermoplastic Sandwich Skin

The warping wing concept was based on avoiding large strains in the skin. Although the warping wing concept was proved to be feasible, it has its limitations. The class of aerodynamically useful wing deformations that can be achieved without significant straining of the skin is limited. This poses the problem of avoiding excessive straining of the skin during morphing. One method to achieve that is to use a thermoplastic skin with embedded heating grid. By applying electric current to the grid, the temperature can be raised above the glass transition temperature of the thermoplastic skin causing the skin to assume a rubber-like state. Thus, a significant reduction of the skin stiffness and an increase in possible strains is achieved. A sandwich construction is proposed to ensure minimum stiffness during morphing and high bending stiffness in non-morphing states as shown in Figure 5.

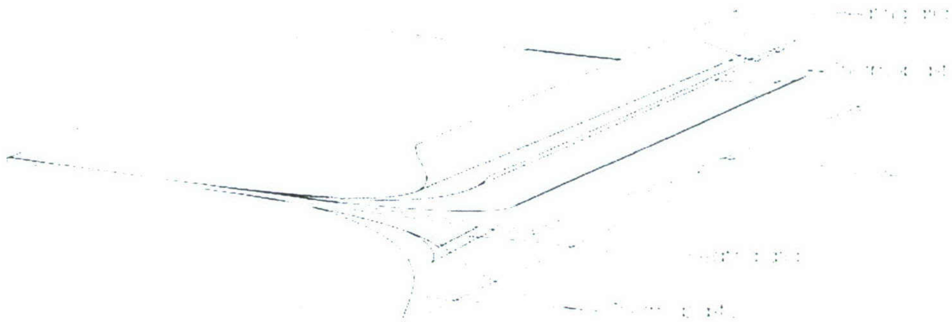


Figure 5: Thermoplastic sandwich skin details.

Tests with various types of thermoplastic materials were performed to identify the optimal skin material for this application. Using a three-point bending test, stiffness properties in cold conditions and at temperatures larger than the material glass temperature were determined. The results are shown in Figure 6.

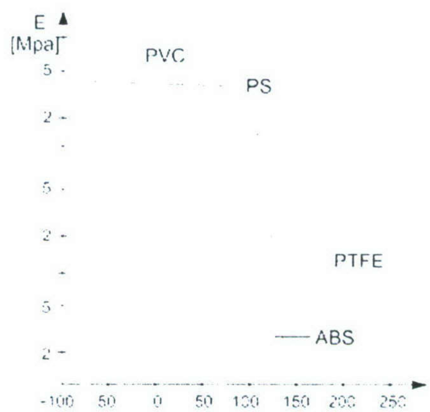
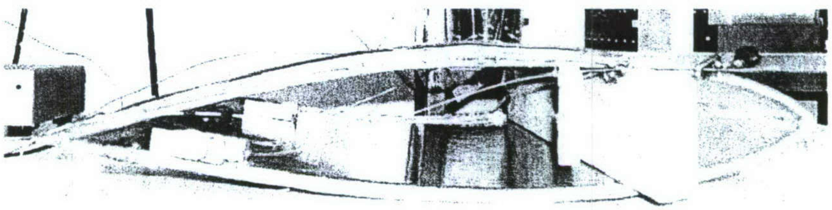


Figure 6: Young's modulus reduction with increased temperature.

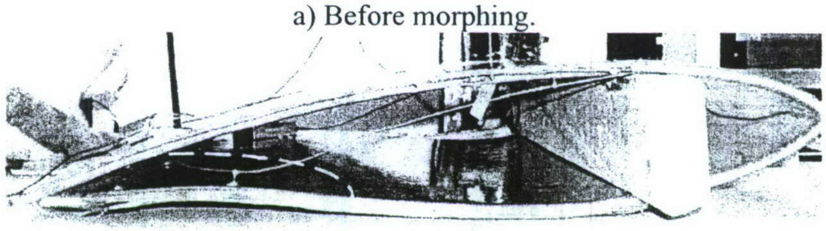
Also different types of core material were investigated. As such, an optimised combination of the sandwich was constructed. The spacing of the heating grid was optimised using numerical

models to make sure there is an optimal trade-off between the required heat delivery to the thermoplastic material and energy consumption. Since the skin is made soft to allow large strains, it is important to take aeroelastic effects into account, since then the structural stiffness is in the order-of-magnitude of the aerodynamic stiffness during morphing. Therefore a two-dimensional panel code was coupled to a two-dimensional structural beam element model to assess the aeroelastic effects. The soft skin appeared not to be able to withstand the aerodynamic loads, however, a solution was provided in the form of the actuator to carry out the morphing manoeuvre. When the skin is in heated condition, the actuation is taken care of by shape memory alloy wires. Their length change during heating of the wires ensures the deformation of the rubber-like skin. Additionally, they also prevent the heated skin from deforming excessively under the aerodynamic loading.

The morphing skin concept was demonstrated for the case of camber changing airfoil. The airfoil was optimised to maximise the lift increment induced by morphing actuation using an SMA wire. The results of test-bench experiments are shown in Figure 7. More details about the test results and experimental design of the morphing skin concept can be found in reference [2].



a) Before morphing.



b) After morphing.

Figure 7: Morphing using thermoplastic sandwich skin.

Analysis of Diamond Cell Mechanisms:

Another concept for morphing wings is NextGen's Batwing shown in Figure 8.

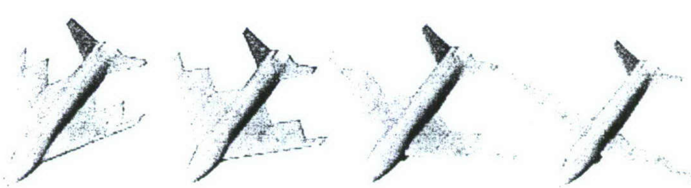


Figure 8. NextGen Batwing Concept

The Batwing is composed of unit cells linked together. A model of the Batwing concept composed of six unit cells is shown Figure 9.

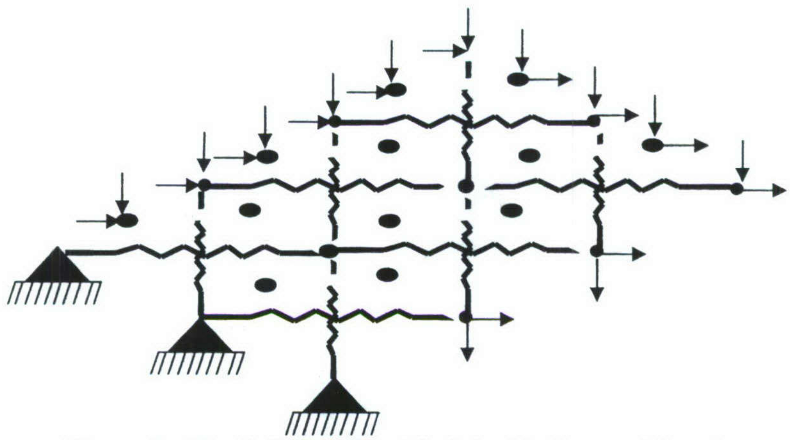


Figure 9. Six Cell Batwing Model with External Loads

The green elements are the links of the mechanism, the red elements are the actuators, and the springs model the stiffness of the skin. In the finite element model the links are modeled by frame elements (3 DOF per node) that are equivalent in length and connected by pin joints. A nonlinear large displacement analysis was conducted considering both actuator and aerodynamic loads The results are summarized in Figure 10.

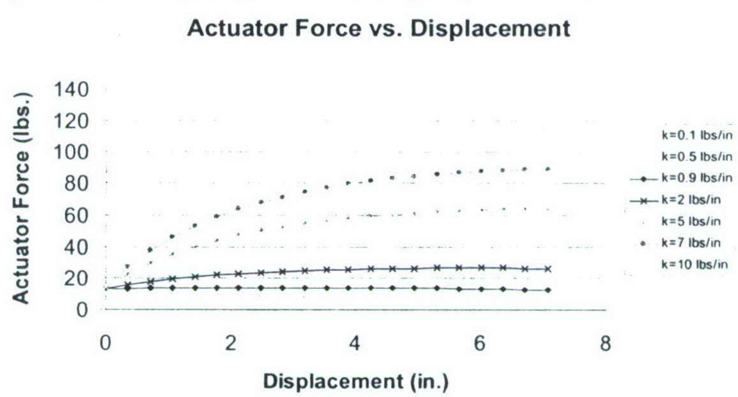


Figure 10. Actuator Force vs. Output Displacement

A design optimization procedure has been developed to maximize the energy efficiency of a scissor mechanism [3]. The goal of this work is to study the affect of optimal actuator placement on energy efficiency. We define energy efficiency η as the ratio of output work to input work, and the objective of the optimization is to maximize energy efficiency η subject to a constraint on x (Equation 1).

$$\max \quad \eta = \frac{-\left(\sum F_{ex} X_{out} + \sum F_{ey} Y_{out}\right)}{\sum F_{Act} \Delta}$$

$$s.t. \quad 10\% \leq x \leq 95\% \tag{1}$$

The quantity X_{out} is the x-directed displacement done against external load F_{ex} and Y_{out} is the y-directed displacement done against external load F_{ey}. The quantity F_{Act} represents the input force exerted on the unit cell by an actuator. The quantity Δ is the displacement of the actuator in the unit cell.

A two stage optimization process using a Genetic Algorithm and traditional gradient based optimization (FMINCON) was developed to optimize actuator position and placement for different constraints and load cases. The effect of the number of actuators allowed in the two-stage optimization on energy efficiency is shown in Figure 11, where the red lines indicate the actuators in their optimized positions. It can be observed that limiting the number of actuators does not drastically affect the overall energy efficiency. It can also be observed that the actuator positions tend toward one of the limits in each case.

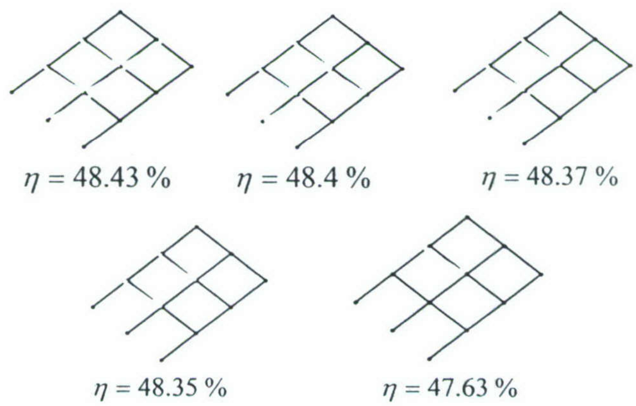


Figure 11. Optimization Results.

Results of a study on the affect of the stiffness of the skin for a design with one actuator are shown in Figures 12 and 13.

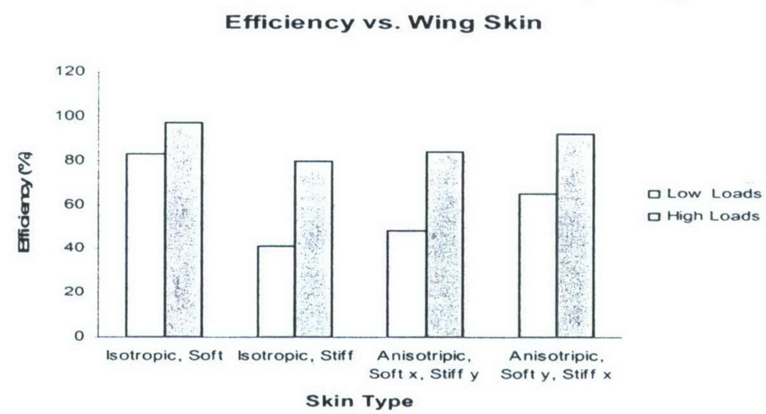


Figure 12. Efficiency vs. Wing Skin

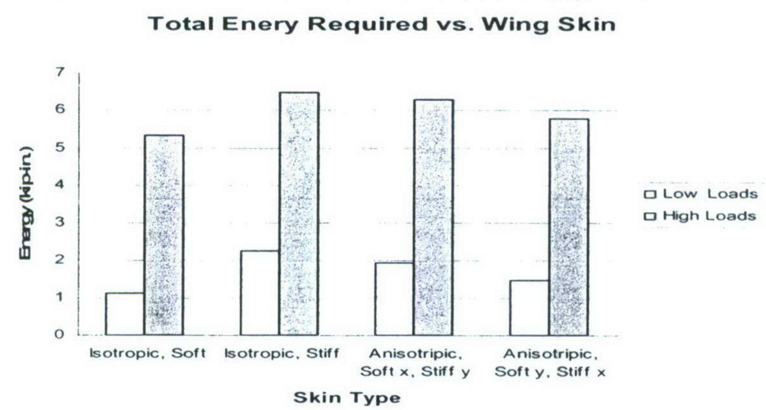


Figure 13. Total Energy Required (Input Energy) vs. Skin Stiffness

It can be observed that morphing under high loads is more efficient than morphing at low loads regardless of the skin stiffness, and that morphing under high loads requires more input energy than morphing under low loads. In addition morphing using a soft isotropic skin is more efficient than stiff isotropic and anisotropic skin.

Aeroelastic Analysis and Optimisation of Morphing Wings

To complement the analysis and optimization of the diamond cell mechanism, preliminary aeroelastic analysis of sweep change manoeuvres is carried out. A tool has been developed for the aeroelastic energy-based analysis of morphing wings, which is able to analyse the energy requirements to morph a wing that undergoes a considerable change in shape, including both elastic and rigid body deformations [4]. In this analysis, aeroelastic deformations and aerodynamic forces, aiding or counteracting the actuation forces, are taken into account. The mathematical tool is based on a six degree-of-freedom beam model with arbitrary composite cross-section in a co-rotational framework, accounting for nonlinear large deformations. For

aerodynamic modelling, a vortex lattice method based on Prandtl's lifting line theory is used, with a spanwise panel distribution. Sample results for sweep-change morphing are shown in Figure 14.

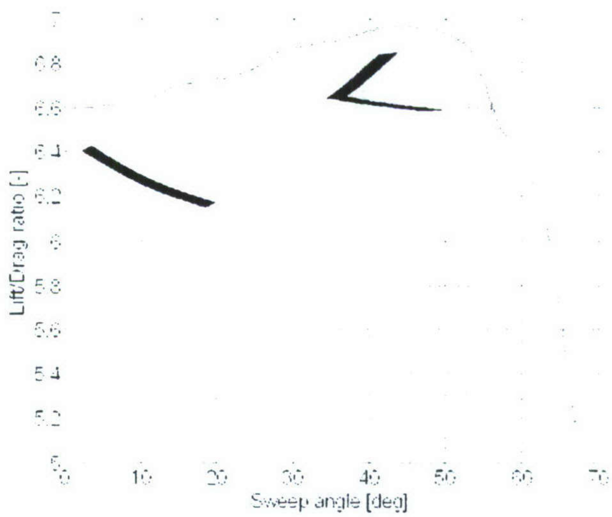


Figure 14: Aerodynamic characteristics change during wing morphing.

For the parameters used, an optimum sweep angle of 45 degrees gives the maximum lift to drag ratio. This tool can be used for tailoring the hinge locations for segmented wings [5]. This possibility is currently under investigation.

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